The deforestation of Easter Island

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ABSTRACT

Easter Island deforestation has traditionally been viewed as an abrupt island-wide event caused by the prehistoric Rapanui civilization, which precipitated its own cultural collapse. This view emerges from early palaeoecological analyses of lake sediments, which showed a sudden and total replacement of palm pollen by grass pollen shortly after Polynesian settlement (800-1200 CE). However, further palaeoecological research has challenged this view, showing that the apparent abruptness and island-wide synchronicity of forest removal was an artefact due to the occurrence of a sedimentary gap of several millennia that prevented a detailed record of the replacement of palm-dominated forests by grass meadows. During the last decade, several continuous (gap-free) and chronologically coherent sediment cores encompassing the last millennia have been retrieved and analysed, providing a new picture of forest removal on Easter Island. According to these analyses, deforestation was not abrupt but gradual and occurred at different times and rates, depending on the site. Regarding the causes, humans were not the only factors responsible for forest clearing, as climatic droughts as well as climate-human-landscape feedbacks and synergies also played a role. In summary, the deforestation of Easter Island was a complex process that was spatially and temporally heterogeneous and took place under the actions and interactions of both natural and anthropogenic drivers. In addition, archaeological evidence shows that the Rapanui civilization was resilient to deforestation and remained healthy until European contact, which contradicts the occurrence of a cultural collapse. Further research should aim to obtain new continuous cores and make use of recently developed biomarker analyses to advance towards a holistic view of the patterns, causes and consequences of Easter Island deforestation.

Key words: Rapa Nui, forest clearing, cultural collapse, last millennium, climate change, drought, fire, human disturbance, agriculture, pollen analysis.

CONTENTS

I. INTRODUCTION

Deforestation is a common feature linked to human settlement of forested areas. Oceanic islands are particularly sensitive to deforestation because of the difficulty of forest regeneration resulting from the physical isolation that prevents recolonization from other potential forest sources. Therefore, deforestation of oceanic islands is often irreversible. The case of Easter Island (Rapa Nui), the easternmost Polynesian island and one of the most remote inhabited places on Earth (Fig. 1), has become iconic, as it has been considered an example of a cultural collapse purportedly caused by human overexploitation of natural resources, including the total removal of palm forests that dominated the island before human settlement. This cultural collapse of the ancient Rapanui civilization has been called ecocidal and has been used as a microcosmic model of the whole planet under current exploitation practices (Bahn & Flenley, 1992; Flenley & Bahn, 2003; Diamond, 2005). Other researchers have proposed that the deforestation was caused by extensive palm fruit consumption by Pacific rats (*Rattus exulans*), which would have hindered forest regeneration (Hunt, 2006, 2007). These rats were carried to the island by the first Polynesian colonizers, whose arrival occurred between approximately 800 CE and 1200 CE, according to different authors (Flenley & Bahn, 2003; Hunt & Lipo, 2006; Vargas et al., 2006; Wilmshurst et al., 2011; Mieth & Bork, 2015). According to this view, deforestation did not cause a cultural collapse, and the ancient Rapanui culture remained healthy until the arrival of the first Europeans (1722 CE), when the degradation of the Rapanui culture initiated and the culture finally collapsed due to slave trading and the introduction of alien epidemic diseases (Rainbird, 2002; Peiser, 2005). Regardless of the cause, the island was completely deforested when the first Europeans arrived in 1722 CE (Zizka, 1991). This date (1722 CE) is usually considered the boundary between prehistoric and historic times on Easter Island.

Different timings and rates of deforestation on Easter Island have been proposed. The first estimations assumed that forest clearing took place over 600 years, between 800 CE and 1400 CE (Flenley & Bahn, 2003). As the surface area of the island is 164 km^2, the deforestation rates would have been approximately 0.27 km^2 per year (km^2/y). Others proposed that deforestation occurred over 370 years (1280 CE to 1650 CE) (Mann *et al.*, 2008), which results in an estimated rate of 0.44 km^2/y. These estimations were based on palaeoecological data and pollen analyses of lake sediments. Other estimations, based on archaeological evidence, result in similar rates, as these data suggest that forest removal spanned approximately 400 years (1200 CE to 1600 CE) (Hunt, 2006, 2007), yielding estimates of 0.41 km^2/y. If we consider that forests did not cover the whole island but approximately 80% of its surface (Mieth & Bork, 2015), these estimates should be reduced by 20%, which yields a range between 0.22 and 0.35 km^2/y. Although deforestation of Easter Island is commonly viewed as a relatively rapid and abrupt process, these rates are slow compared to the current worldwide estimates of forest removal of 52,000 km^2/y between 2000 and 2010 (FAO, 2012). At such rates, Easter Island would have been deforested in about a single day. It has also been proposed that deforestation was not a single continuous event but occurred in two phases. The first phase, between about 800 CE and 1250-1350 CE, would have been dominated by woodland gardening and the small-scale cutting of trees, with low-intensity forest disturbance. During the second phase, starting at 1250-1350 CE, forest clearing would have intensified, leading to total forest removal, which would have occurred up to 1650 CE.

This hypothesis is based on an island-wide study of dated slash-and-burn events (Mieth & Bork, 2015) and is supported by palynological and wood macrocharcoal analyses (Orliac et al., 2000; Mann et al., 2008).

Before European contact, the Rapanui people were unaware of metals. The typical megalithic anthropomorphic cult statues (moai) that characterized the ancient Rapanui culture (Fig. 2), still present and widespread across the island, were carved from soft tuff using instruments made of a harder basalt called toki (Gioncada *et al.*, 2010; Simpson & Dussubieux, 2018). Other instruments consisted of obsidian bladed points with cutting edges (mata'a), which were first interpreted as spear points or similar weapons; however, recent studies suggest that they were used for more peaceful labours such as cultivation, ritual scarification (Lipo *et al.*, 2016) and, notably, forest clearing, in combination with basalt adzes (Stevenson & Williams, 2018). Fire was also intensively used for deforestation, as supported by palaeoecological records of charcoal increases associated with palm removal (Mann *et al.*, 2008; Butler & Flenley, 2010; Horrocks *et al.*, 2012a, b, 2015). Several reasons for deforestation of the island have been proposed, such as collecting firewood or wood for building dwellings and boats, opening land areas for cultivation or obtaining rolls for moai transportation, among others (Flenley & Bahn, 2003).

The first sound evidence for the existence of former forests on the island emerged from incipient palynological studies of lake sediments. The first available record of past woody vegetation consisted of pollen analyses from sediments of unknown age obtained by Thor Heyedahl during his 1955-56 expedition. These analyses were performed by palynologist Olof Selling but remain unpublished. The only available mention of these analyses is by Heyerdahl, who cited personal communication with Selling, who reported the common presence of pollen from composite species and possibly one palm species that is now extinct (Heyerdahl & Ferdon, 1961). Approximately 20 years later, John Flenley and his collaborators published the first systematic pollen records from sediment cores retrieved from the ~40,000-year-old sediments of the three permanent freshwater bodies on the island: the Aroi marsh and the lakes Kao (or Kau) and Raraku (Fig. 3). These analyses clearly demonstrated the continuous presence of palm-dominated forests until the last millennia, when they were replaced by grass meadows (Flenley & King, 1984; Flenley *et al.*, 1991). These results became paradigmatic and were (and still are) used to sustain the ecocidal hypothesis of the collapse of the ancient Rapanui culture.

Further research, however, has challenged this view and has suggested new scenarios for Easter Island's prehistory. This paper reviews the developments of palaeoecological research since Flenley's pioneer studies, with an emphasis on the potential causes of forest clearing and the spatiotemporal deforestation patterns. Relevant research questions include the following: was the deforestation abrupt or gradual? Was the deforestation synchronous and island-wide, as proposed by the pioneer studies? Or, on the contrary, did the deforestation occur at different times and at different rates, depending on the site? Was the deforestation entirely anthropogenic? Did environmental change play some role in forest clearing? This review begins with a characterization of the dramatic vegetation shift from the former forests to the modern-like open vegetation. Then, the spatiotemporal deforestation patterns are analysed, and finally, the potential causes of such patterns are discussed, with an emphasis on human activities and environmental change. It should be stressed that this paper uses and discusses primarily paleoecological evidence as the most straightforward evidence for environmental and ecological changes, which are the targets of the review. When necessary, pertinent archaeological and historical data are also used, albeit not discussed in depth. To facilitate reading, the first section places the topic in a historical context by briefly summarizing the main cultural developments between the island's settlement and European contact, on the basis of the archaeological, anthropological and ethnological evidence collected to date.

II. HUMAN SETTLEMENT AND MAIN CULTURAL DEVELOPMENTS

The issue of Easter Island's settlement by humans is complex and has been thoroughly reviewed elsewhere (Rull, 2019a). The consensus is that the prehistoric Rapanui civilization that built the moai originated from Polynesian navigators, who probably arrived from the Gambier or the Marquesas Islands (Fig. 1) (Routledge, 1919; Métraux, 1940), but the time of arrival is still debated. Based on archaeological evidence, the arrival dates range between ~400 CE (Heyerdahl & Ferdon, 1961) and ~1300 (Wilsmhurst et al., 2011), although the most accepted range is between 800 CE and 1200 CE (Flenley & Bahn, 2003; Kirch, 2010). The finding of remains of sweet potato (*Ipomoea batatas*) – an American plant considered the main food source during the flourishment of the prehistoric Rapanui society, between 1200 CE and 1500 CE (Fischer, 2005; McCall, 2009) – opened the possibility of an Amerindian influence long before European contact. The presence of Amerindians (or Native Americans) on Easter Island before European contact, even before the Europe-America contact, has been supported by dietary, DNA and craniometric analyses of modern and ancient Rapanui and associated flora and fauna (e.g., Storey et al., 2007; Moreno-Mayar et al., 2014; Tromp & Dudgeon, 2015; Thorsby, 2016). However, with the available evidence, it is not possible to know whether these Americans arrived at Easter Island by themselves or were carried by Polynesians in eventual back-and-forth voyages to South America (Rull, 2019a).

Archaeological and ethnological evidence indicates that during the first few centuries of Easter Island's settlement, the entire Rapanui society was organized around the moai industry, and >950 moai and 300 ahus (the stone platforms where the moai were emplaced in groups) were built (Van Tilburgh (1994). The moai represented deified ancestors and were worshiped to guarantee land/sea fertility and, hence, social prosperity. This form of cult has been called the Ancient Cult or the Moai Cult (Edwards & Edwards, 2013). During the Moai Cult, the centre of the Rapanui society was the Raraku crater, which supplied the tuff from which the moai were carved, but all coastal areas were settled, and the society was organized into territorial clans (Routledge, 1919). Total population estimates during the flourishment of the Rapanui society and the moai industry (i.e., 1200 CE to 1500 CE) range between about 3000 and 20,000 people, but the most common values are 6000-8000 people for the whole island (Flenley & Bahn, 2003). At some point, which is still debated, the Moai Cult was replaced by the Birdman Cult, which involved completely different religious, political and social reorganizations (reviewed in Robinson & Stevenson, 2017). In the Birdman Cult, the symbols of fertility were the migratory birds, specifically the sooty terns (*Onychoprion fuscatus*), that used to nest on the island's surrounding islets. The perennial and dynasty-based hierarchy of the Moai Cult disappeared, and the highest authority of the island was elected each year from among the clan chiefs on the basis of an athletic competition to obtain the first egg of the sooty terns that nested on the Motu Nui islet. This islet was situated in front of the ceremonial village of Orongo, where the athletic competition started, located on the SW crest of the Kao crater (Fig.3). In this way, Orongo became the new geographical centre of the Rapanui culture. According to archaeological evidence, Orongo was founded no earlier than 1600 CE (Robinson & Stevenson, 2017); therefore, the replacement of the Moai Cult by the Birdman Cult would have occurred by 1600 CE or later. The end of the moai industry would have been due to the difficulty of carving the hard basalts of the Kao crater – where the carving tools (toki) were commonly obtained (Gioncada *et al.*, 2010; Simpson & Dussubieux, 2018) – with the ancient Rapanui technology. Only a dozen basaltic moai are known (Van Tilburgh, 1994).

Some authors relate the shift from the Moai Cult to the Birdman Cult to internal wars and social conflicts (Routledge, 1919; Métraux, 1940; Mulloy, 1979). This idea is based on Rapanui legends, the assumption that many moai were deliberately toppled and the finding of the abovementioned obsidian blades (mata'a), which were interpreted as spear points. However, recent archaeological evidence does not support these interpretations (Lipo et al., 2016; Stevenson & Williams, 2018). The defenders of the ecocidal view

considered the hypothetical social conflicts to be the results of resource exhaustion (including deforestation) and to have caused the population decline and the cultural shift that led to the collapse of the ancient Rapanui society (reviewed in Flenley & Bahn, 2003). However, as mentioned above, the Rapanui society was resilient to deforestation and subsisted without significant population declines until European contact (Hunt & Lipo, 2011).

III. FROM ANCIENT FORESTS TO PRESENT-DAY VEGETATION

Easter Island's forests were completely removed without leaving a trace, and there is no living witness of their composition and physiognomy. Everything we know about these ancient forests has been inferred from pollen and fossil wood analyses and knowledge of the modern features of the involved taxa. The dominant palm species, however, could not be identified. Human introductions have been significant, especially after European contact; therefore, the present-day vegetation is very different from the vegetation that grew on the newly deforested island. This section briefly summarizes the available knowledge of the early forest composition and the main features of the modern vegetation, with notes on the main crops of the ancient Rapanui civilization and the historical post-contact human introductions.

(1) The ancient forests

The first inferences based on pioneer pollen analyses (Flenley & King, 1984; Flenley *et al.*, 1991) provided a general picture of the forest composition, which has not changed over time. The abundance of palm pollen in sediments (typically 40-70% in Raraku and Kao) strongly suggested that these forests were dominated by one palm tree species, but the commonness of the pollen type within the palm family prevented identification at the genus or species level (Fig. 4). An early detailed morphological analysis suggested that the pollen belonged to some species of the Cocosoidae subfamily, which is represented in the Pacific region by the widespread *Cocos nucifera* (coconut) and *Jubaea chilensis* (Chilean wine palm), which inhabits the Pacific Chilean coasts (Dransfield *et al.*, 1984) (Fig. 5). Further discoveries of palm nut endocarps that were significantly smaller than those of coconuts and trunk and root casts that were similar to those of *Jubaea* seemed to support the second possibility (Grau, 1998, 2001). However, this analogy was questioned based on the conspicuous environmental differences between Easter Island and the Chilean coasts, and a possible affinity with *Juania australis*, an endemic palm of the Juan Fernández Islands, was suggested (Hunter-Anderson, 1998). Based on endocarp morphology, a new monospecific genus was described for the Easter Island palm called *Paschalococos disperta*, which is thought to be extinct (Zizka, 1991). A further phytolith analysis again revealed morphological similarities with *J.chilensis,* but a detailed statistical analysis of the morphometric characters of the phytoliths suggested the possibility that more than one palm species grew on the island (Delhon & Orliac, 2007).

Palm pollen occurred together with pollen from several shrubs, which suggested the existence of a shrubby understory whose main components would have been *Sophora* (Fabaceae), *Triumfetta* (Tiliaceae), *Macaranga* and *Acalypha* (Euphorbiaceae), *Coprosma* (Rubiaceae) and several unidentified Asteraceae, Myrtaceae and Urticaceae/Moraceae species (Flenley & King, 1984; Flenley *et al.*, 1991) (Fig. 4). The occurrence and abundance of these elements vary in space and time, but they seem to have been usual components of palm-dominated forests. An interesting finding was charcoal fragments corresponding to >20 woody taxa, which were found at three archaeological sites, with ages ranging from the early 14th to the mid-17th century (Orliac, 2000; Orliac & Orliac, 1998). It has been asked whether these taxa were part of the ancient forests, as suggested by the age of their charred remains. However, only four of these taxa (*Triumfetta, Sophora, Coprosma,* and *Paschalococos*) have been found in previous palynological studies. The

remaining taxa, notably, *Caesalpinia* (Caesalpiniaceae), *Thespesia* (Malvaceae), *Broussonetia* (Moraceae), *Sapindus* (Sapindaceae), *Psydrax* (Rubiaceae), *Elaeocarpus* (Elaeocarpaceae), *Myrsine* (Myrsinaceae), *Syzygium* (Myrtaceae), *Pittosporum* (Pittosporaceae), *Alphitonia* (Rhamnaceae) and *Premma* (Verbenaceae), are absent from palynological records, suggesting that they were not part of the ancient forests. However, the absence of these species, or part of them, from pollen records could also be due to low pollen production and/or dispersal capacity, rather than to their absence in former forests. This situation is usual in plants pollinated by animals (zoophilous) rather than by wind (anemophilous) (Faegri & Van der Pijl, 1979). Alternative explanations are that these taxa were planted by Polynesian colonizers or were driftwood fragments that were utilized as firewood (Zizka, 1991).

In addition to forest composition, forest cover has also been discussed. Although not explicitly stated, the first palynological works seemed to implicitly assume that Easter Island was entirely forested. The first (and the only available to date) quantitative estimation of forest cover was based on the present spatial distribution of root casts and charred palm trunks. An extrapolation of the density of these features in the better-preserved sites indicated that, prior to deforestation, approximately 80% of the island would have been covered by dense forests containing almost 20 million palm trees (Mieth & Bork, 2015, 2017) (Fig. 5). A different view considered that the pollen signal was compatible not only with a fully (or mostly) forested island but also with other scenarios, including a mosaic vegetation pattern with forests restricted to sites with permanent freshwater such as lakes, marshes and coastal areas with high freshwater tables (Rull *et al.*, 2010). The lack of modern analogues for these forests and the uncertain identity of the extinct palm that dominated them prevent a sound reconstruction of the Easter Island landscape prior to deforestation.

(2) Prehistoric agriculture

After Polynesian settlement (800 to 1200 CE), Easter Island's forests coexisted with crops (Mieth & Bork, 2005). It has also been suggested that the forest was managed to obtain palm sap for sugar and other nutritious substances, but this suggestion was based on the modern use of *Jubaea chilensis* in central Chile and needs empirical confirmation (Bork & Mieth, 2003). Archaeological evidence has shown that the ancient Rapanui did not practice extensive cultivation or widespread irrigation; crops were restricted to small (metre-scale) garden features called *manavai*, whose water supply was heavily dependent on rainfall (Hunt & Lipo, 2011; Puleston *et al.*, 2017). To minimize evaporation and erosion, the *manavai* were protected from wind and surficial runoff by rock walls up to 2 m high, and soils were covered by rocks to preserve heat, moisture and nutrients, a practice called lithic mulching (Stevenson *et al.*, 1999; Wozniack, 1999; Gossen & Stevenson, 2005). Chemical analyses of agricultural soils suggest that they were more nutrient-rich than non-gardened soils, likely due to mulching-reduced leaching or active release of household organic matter (Hunt & Lipo, 2011; Ladefoged *et al.*, 2010). The first estimations using satellite imagery identified more than 2500 *manavai*-like cultivation structures, for a total of 16.5 km^2, which represents 10% of the island's surface (Hunt & Lipo, 2011). Later, these estimates were increased to 13% of the coastal zone and 19% of the island surface (Ladefoged *et al.*, 2013). During the first 500 years of human occupation, cultivation was carried out along the coasts and 1-2 km inland, and the main volcanic peaks (Kao, Pike and Terevaka) were likely forested; however, after ~1500 CE, these forests were also replaced by *manavai* structures (Mieth & Bork, 2005). Recent investigations have shown that these agricultural practices continued, with no significant decline, until European contact (Mulrooney *et al.*, 2013; Mieth & Bork, 2015,2017; Stevenson *et al.*, 2015; Jarman *et al.*, 2017). In addition to these main dryland cultivation practices, palaeoecological evidence for local terrace cultivation has also been found on the shores of wetlands, such as lakes Kao and Raraku and the Aroi marsh, where local irrigation systems possibly existed (Horrocks *et al.*, 2012a, b, 2015).

Microfossil (pollen, phytolith, and starch) analysis of both dryland soils and wetland sediments has allowed the identification of the main plants of Polynesian origin that were cultivated prior to European contact, including mahute or paper mulberry (*Broussonetia papyrifera*; Moraceae), taro (*Colocasia esculenta*; Araceae), ti (*Cordyline fruticosa*; Asparagaceae), yam (*Dioscorea alata*; Dioscoreaceae), kumara or sweet potato (*Ipomoea batatas*; Convolvulaceae), ipu kaha or bottle ground (*Lagenaria siceraria*; Cucurbitaceae) and maika or banana (*Musa* sp.; Musaceae) (Horrocks & Wozniak, 2008; Horocks *et al.*, 2016). The first Europeans who landed on Easter Island in 1722 documented the cultivation of bananas, sweet potatoes, yams and sugar cane (*Saccharum officinarum*; Poaceae). The case of sweet potato is especially interesting, as mentioned above (section II).

(3) Modern vegetation

According to the available pollen records, deforested lands were initially covered by extensive, species-poor grass meadows, with aquatic or semiaquatic plants – mainly sedges of *Scirpus* and *Polygonum* (Polygonaceae) - in flooded terrains (Flenley & King, 1984; Flenley *et al.*, 1991). Today, the situation is very different as post-contact introductions and land management have deeply changed the island's ecosystems, leading to a fully anthropogenic landscape. Detailed accounts of historical developments and landscape transformations are available elsewhere (McCall, 1981; Fischer, 2005; Hunt & Lipo, 2011). Today, the island is largely covered by grass meadows (90%), with very low forest (5%) and shrubland (4%) cover, and pioneer and urban vegetation represent 1% of the surface (Etienne *et al.*, 1982). Most meadows are dominated by two widely distributed grasses, namely, *Sporobolus indicus* and *Paspalum scrobiculatum*, but the Terevaka uplands are dominated by the endemic grass *Axonopus paschalis* (heriki hare). Most forests are recent plantations of *Eucalyptus* spp. (Myrtaceae), which was also introduced from Australia, and *Dodonaea viscosa* (Sapindaceae), carried from tropical America, as well as the native *Thespesia populnea* (Malvaceae). Shrublands are largely dominated by the invasive *Psidium guajava* (Myrtaceae), also introduced from tropical America. Wetlands are dominated by *Scirpus californicus* (Cyperaceae) and *Polygonum acuminatum* (Polygonaceae), both also occurring in tropical America.

The angiosperm flora of the island is composed of ~180 species, of which 17% are autochthonous, 79% are introduced, and the remaining 4% are of uncertain origin. Among the introduced species, almost half (~48%) are considered to be naturalized. Globally, the families with the most species are Asteraceae and Fabaceae. Only 4 extant species are considered endemic to the island: *Axonopus paschalis* (Poaceae), *Danthonia paschalis* (Poaceae), *Sophora toromiro* (Fabaceae), and probably *Paspalum forsterianum* (Poaceae) (Zizka, 1991). Among them, the toromiro (*S. toromiro*) is considered to have been extinct in its natural habitat for the past 50 years and is maintained only by cultivation on the island and in several botanical gardens elsewhere (Maunder *et al.*, 2000). Given the isolation of Easter Island, the ways in which the autochthonous species reached the island are of special significance. Interestingly, none of the autochthonous angiosperms have the potential for wind dispersal, and the main dispersal mechanisms are transport by birds (75%) and drifting through seawater (25%) (Carlquist, 1967, 1974).

IV. SPATIOTEMPORAL DEFORESTATION PATTERNS

On Easter Island, there are only three volcanic craters containing permanent freshwater and sediments suitable for palaeoecological studies. These ranos (local term to designate a volcanic crater with a permanent body of freshwater inside) are widespread across the island and situated at different elevations, from the coastal lowlands to the inner uplands, thus covering a wide range of environmental conditions. Therefore, an integrated palaeoecological study of these three sites can provide a general island-wide picture of long-term ecological trends. This section briefly explains the available pollen records for the last

millennia to disclose the timing and rates of deforestation for each rano and its surroundings in order to obtain an island-wide picture.

(1) Rano Raraku

Rano Raraku contains a relatively small and shallow lake (~300 m diameter, 2-3 m depth) situated at an 80 m elevation in the eastern coastal lowlands. The sedimentary infill is at least 14 m deep, which corresponds to an age of 34 cal kyr BP (Rull, 2016b). This lake has historically been the preferred site for Easter Island's palaeoecological studies for several reasons. First, the lake is highly accessible, and coring equipment can be easily transported to the site. Second, the most chronologically coherent stratigraphic sequences have been obtained from this lake, whereas in Aroi and Kao, frequent age inversions have usually prevented the development of suitable age-depth models (Butler & Flenley, 2010; Horrocks *et al.*, 2012a, b, 2015). Third, the more evident patterns of replacement of palm forests by grass meadows have been recorded in Raraku sediments. The drawback related to this site is that the sedimentary records retrieved until a decade ago have an extensive stratigraphic gap that encompasses several millennia, including the time of interest for island deforestation. This gap is considered the main reason why the first palynological records of deforestation appeared to be abrupt (Rull *et al.*, 2013). In the first records, this gap was 7 millennia or more, extending from >7.5 cal kyr BP to approximately 0.5 cal kyr BP (Flenley & King, 1984; Flenley *et al.*, 1991; Dumont *et al.*, 1998). Further studies reduced the gap to approximately 3500 years (~4 cal kyr BP to ~0.5 cal kyr BP) (Mann *et al.*, 2008; Sáez *et al.*, 2009), but the last millennia, when the island was deforested, remained hidden. A more recent palynological analysis showed abrupt deforestation and equally rapid grass expansion between 1.86-1.63 cal kyr BP and 0.63-0.51 cal kyr BP, coinciding with a sudden increase in charcoal, which is a proxy for fire, and the first signs of terrace cultivation using taro, sweet potato, banana and possibly bottle gourd (Horrocks *et al.*, 2012a). In this case, the sedimentary gap occurred just before those dates and spanned approximately 8000 years.

An almost continuous and chronologically coherent Raraku sequence (RAR-08) was retrieved a few years later, which encompassed the last 3.7 cal kyr and included only two minor centennial-scale gaps (Cañellas-Boltà *et al.*, 2013) (Fig. 6). This sequence showed that the first deforestation event took place approximately 450 BCE and proceeded gradually until ~1550 CE, with two major accelerations: one at ~1200 CE and another at ~1450 CE (Fig. 7). Forest retraction was continuous, and no regeneration phases were observed. The grass meadows followed an inverse trend paralleled by charcoal trends. Fire incidence was low until ~1200 CE, when it significantly increased in parallel with the major deforestation pulse. The grass and fire trends largely coincided with the trends of *Verbena litoralis* (Verbenaceae) (Fig. 4), which is a weed of American origin, suggesting that humans were actively involved in island deforestation. The potential significance of *V. litoralis* for the colonization timing and origin of the first settlers is discussed elsewhere (Rull, 2019a). This reconstruction supported the view that the previously assumed abruptness of forest clearance was an artefact caused by the large sedimentary gap in the previous sequences. Using the palm pollen percentage as a rough estimate of the forest cover, the latest Raraku record suggests that deforestation proceeded at a general rate of approximately -4% per century (Rull *et al.*, 2015), which is far from instantaneous. If we consider only the last millennium, when deforestation rates significantly accelerated, the rates increase to -9% per century.

(2) Rano Aroi

Rano Aroi is a mire ~150 m in diameter that is situated at a 430 m elevation in the northern Terevaka uplands. The mire infill is predominantly peat and is at least 16 m thick in the centre, which represents an extrapolated age of approximately 70,000 years (Rull, 2016b). The first Aroi records did not show the palm

dominance observed in Raraku for the last ~40,000 years; therefore, no deforestation events were recorded. The whole record was dominated by grasses, followed by some ferns and shrubs, and it was suggested that palm forests were restricted to lowlands and Aroi was near the uppermost treeline, where palm trees were scattered among shrublands and marshes (Fenley & King, 1984; Flenley *et al.*, 1991). In addition, no dates before ~2 ^{14}C kyr BP were measured, which was interpreted to be a result of vertical sediment mixing due to human disturbance in the search for freshwater. As a consequence, the usefulness of the Aroi sediments in reconstructing the vegetation history of the last millennia was questioned (Fenley & King, 1984; Flenley *et al.*, 1991), and the site was not further cored for approximately three decades.

A recent sedimentary sequence confirmed the former interpretation of the near-treeline vegetation (although palms were more abundant than indicated in previous analyses), and a fairly consistent chronology was obtained for the last 1000 years but not for the former 11 millennia, for which age inconsistencies were frequent (Horrocks *et al.*, 2015). Unfortunately, the temporal resolution of the last millennium (one in four samples, or one sample every 250 years) was not enough for a detailed reconstruction. Despite this condition, the first signs of terrace cultivation were dated to ~280 cal yr BP (1670 CE). Cultivated plants included taro, paper mulberry and banana, but sweet potato was remarkably absent, likely due to elevation. Another sedimentary sequence covering the last ~1500-1300 cal kyr BP was obtained in a small swamp near Rano Aroi (Rano Aroi Iti). During this time, meadows were dominant and experienced a slight increase paralleled by a similarly sized forest decline. Charcoal was present throughout the core, but no evidence of cultivation was found. Pollen of the American herb *Sisyrinchium* (Iridaceae) was present since the beginning and occurred throughout the core, suggesting that this plant was introduced by 450-650 CE, more than one millennium before European contact (Horrocks *et al.*, 2015). This case is similar to that of *Verbena* in Rano Raraku (Cañellas-Boltà *et al.*, 2013), and the same considerations of the first Easter Island settlers and the Polynesian discovery of America are valid here.

A fully continuous and chronologically coherent sedimentary record was obtained later in Aroi (ARO08-02), encompassing the last 2.7 cal kyr, which was analysed at a multidecadal resolution (Rull *et al.*, 2015) (Fig. 6). The general dominance of open grass vegetation with palms and shrubs was again confirmed, but this pattern markedly changed during the last several centuries (Fig. 7). Indeed, palm forests underwent a rapid expansion (50% of palm pollen per century) starting at ~1400 CE and peaked slightly after 1500 CE, which coincided with a similarly sized decrease in grasslands, indicating that the site was rather forested. The deforestation began by 1520 CE and was complete ~80 years later, by 1600 CE, coinciding with an abrupt increase in fire that ceased when the site was fully deforested and covered by grassland meadows (Rull *et al.*, 2015). During this event, forest clearing proceeded at a rate of over -70% of palm pollen per century, which is ten times the rate that occurred at Raraku.

(3) Rano Kao

Rano Kao contains the largest lake on the island, which is ~1250 m in diameter and is situated at a 110 m elevation on the southwestern end of the island. The surface of this lake is a mosaic of open water and floating mats of aquatic vegetation up to 3 m deep, overlying a water column approximately 10 m deep. The sediments are at least 21 m deep, and their maximum measured age is approximately 34 cal kyr BP (Rull, 2016b). The pioneering analyses by Flenley and coworkers (Flenley & King, 1984; Flenley *et al.*, 1991) were not conclusive due to dating inconsistencies, probably due to the sinking of floating mats and their mixing with lake sediments (Butler *et al.*, 2004). A further core retrieved by the same team (KAO2), covering almost the entire Holocene, was successfully dated and analysed for pollen and charcoal (Butler & Flenley, 2010). Two deforestation events associated with coeval charcoal increases were recorded in this core (one at 1900-1850 cal yr BP (50-100 CE) and another during the last 600 cal yr BP), but their chronology was difficult to

specify due to age inversions. Between these two events, a phase of forest regeneration occurred. Despite the lack of dating precision, the second deforestation event appeared to be consistent with the classic view of deforestation after Polynesian settlement, but the first event occurred between 700 and 1100 years before Polynesian arrival, which adds support to a hypothetical earlier colonization, as suggested by the presence of *Verbena* and *Sisyrinchium* pollen in the Raraku and Aroi sequences, respectively (Cañellas-Boltà *et al.*, 2013; Horrocks *et al.*, 2012a).

The first continuous and chronologically coherent Kao record encompassing the last millennia (KAO05-3A) was obtained from a floating mat (Gossen, 2007); however, pollen analyses similar to those used for Raraku and Aroi and useful in unravelling deforestation patterns are still unavailable. More recently, pollen and other microfossil (phytoliths and starch) and physical (Fourier-transformed infrared or FTIR) microscopic analyses revealed the occurrence of major deforestation events and provided evidence of terrace cultivation, but age inconsistencies prevented the development of a reliable age-depth model (Horrocks *et al.*, 2012b). Recently, another core (KAO08-03) was retrieved from a floating mat and studied palynologically (Rull *et al.*, 2018; Seco *et al.*, 2019) (Fig. 6). This core extended from approximately 1000 to 300 cal yr BP, and its analysis showed a gradual deforestation trend between approximately 1050 CE and 1600 CE, with three main pulses at 1050 CE, 1350 CE and 1600 CE (Fig. 7). The first two pulses were more intense, and forest regeneration trends were recorded between them. After the second pulse, forests almost disappeared but then experienced some recovery, which was interrupted by the 1600 CE deforestation pulse, which permanently removed palm forests from Rano Kao. Overall, this deforestation trend occurred at an average rate of -9% of palm pollen per century, which coincides with the rate observed for Raraku. Taken individually, the three Kao deforestation pulses occurred at rates of -30% to -50%, which are about half the rates recorded for the abrupt Aroi deforestation. The regeneration phases were slower (-5% to -10%). The first deforestation pulse was not associated with a fire increase, the second occurred at the same time as a moderate fire event, and the third took place at the beginning of the major fire event recorded in the diagram. This, together with a similar increase in *Sporormiella* fungal spores, an indicator of human presence (Van Geel *et al.*, 2003), will be discussed in the section that addresses deforestation causes.

(4) Overview

The above discussion clearly shows that the deforestation patterns across the island were spatially and temporally heterogeneous and occurred at different rates at each site. Therefore, the hypothesis of a single and abrupt island-wide deforestation event, as proposed by the classic paradigm, was likely due to sedimentary artefacts, notably, the occurrence of a major gap in the first cores retrieved. The improvement of knowledge on spatiotemporal deforestation patterns was possible after the intensification of lake coring and palaeoecological analyses in the last decade, which resulted in continuous and chronologically coherent sequences of the last millennia for all sedimentary basins of Easter Island. Another interesting finding is that some forests exhibited regeneration trends between consecutive deforestation events. This occurred in Rano Kao and Rano Aroi, although in this case, regeneration was not preceded by a deforestation pulse. In contrast, no forest regeneration was observed in Rano Raraku. This suggests that deforestation pressure was continuous in some places (Raraku) and intermittent in others (Kao), which adds more heterogeneity to the already irregular deforestation scenario. The differences in palm pollen curves among the three sites (Fig. 7) support the palynological signal for forest retraction and regeneration as being representative of local rather than island-wide trends (Rull *et al.*, 2020), as suggested in pioneer palynological studies (Flenley & King, 1984; Flenley *et al.*, 1991). The causes of such a heterogeneous deforestation scenario in time and space should differ from those of a hypothetical single, abrupt and island-wide forest clearance event, as discussed in the next section.

V. NATURAL AND ANTHROPOGENIC DEFORESTATION DRIVERS

It is not unusual to attribute historical socioecological collapses to the action of single punctual causes. Sometimes the assumed causes are singular natural environmental changes that surpass the adaptation capacity of ecosystems and/or human societies (environmental determinism), whereas in other cases, the purported drivers are anthropogenic (human determinism). On Easter Island, human determinism has traditionally been the norm, as deforestation and the Rapanui cultural collapse have been attributed to anthropogenic causes such as prehistoric overexploitation, introduction of exotic species, internal conflicts and wars, and post-contact genocide. Climatic changes have rarely been considered as potential causes of cultural change, but this view has changed during the last decade. In this section, we will analyse the potential role of natural and anthropogenic drivers in the island's deforestation and its cultural consequences. Rather than a shift from human determinism to environmental determinism, this should be viewed as an attempt to consider all possible drivers as well as their interactions in the form of feedbacks and synergies. This methodology has been called the strong fuzzy EHLFS (Environment-Human-Landscape Feedbacks and Synergies) approach and uses a multiple-working-hypotheses framework and the strong inferential method of hypothesis testing (Rull, 2018) (Fig. 8).

(1) Climate change on Easter Island during the last millennia

The lack of empirical evidence of climatic changes on Easter Island was used in the past to dismiss the potential role of climate in the purported prehistoric socioecological collapse (Diamond, 2005). Some authors have speculated about the possible effect of droughts during the Little Ice Age (LIA) (McCall, 1993), the potential influence of ENSO variability on Easter Island (Orliac & Orliac, 1998; Nunn, 2000; Orliac, 2000; Nunn & Britton, 2001; Stenseth & Voje, 2009) or the Late Holocene climatic instability on the disappearance of palm forests (Hunter-Anderson, 1998). Others have denied such a possibility, arguing that the ENSO and other climatic systems do not produce enough variability to significantly affect Easter Island's climate (MacIntyre, 2001; Genz & Hunt, 2003; Junk & Claussen, 2011). However, most of these proposals were based on extrapolations from modern climates, and no palaeoclimatic evidence was available to support either view. The first evidence of a changing climate was obtained by pollen analysis of sediments from Rano Raraku (RRA5) spanning 28 to 10 cal kyr BP, which includes the Last Glacial Maximum (LGM), which was the coldest worldwide event before the Holocene when the average southern Pacific temperatures were up to 6 °C cooler than at present. However, on Easter Island, the LGM estimates based on the Raraku RRA5 core were only ~2 °C cooler than at present (Azizi & Flenley, 2008). It was inferred that if the temperatures of the coolest glacial phase were only 2 °C below the present temperatures, Holocene temperature shifts might have been negligible, and hence, temperature shifts were unlikely to have driven the ecological changes during the last millennium, such as deforestation. However, this did not dismiss the potential influence of eventual moisture changes, mainly droughts, as proposed initially (McCall, 1993).

Further studies interpreted the Raraku millennial-scale sedimentary gap mentioned above as evidence of an extended drought that dried out the lake and could have played a role in deforestation, together with human disturbance (Mann *et al.*, 2008; Sáez *et al.*, 2009). However, the finding of fairly continuous sedimentation in other cores from the same lake challenged this view. In one of these cores (RAR 08), two minor gaps remained that were interpreted as evidence of lake desiccation due to climatic droughts. The first gap occurred between 500 CE and 1200 CE, during the Medieval Climate Anomaly (MCA), and the second took place between 1570 CE and 1720 CE, during the LIA (Cañellas-Boltà *et al.*, 2013). The sedimentation was continuous in Rano Aroi, but two phases of vegetation opening occurred well before human settlement and were not associated with fire events, suggesting the occurrence of two phases of dry

climates at 300 BCE-50 CE and 600-1100 CE, with the latter coinciding with the MCA drought recorded at Raraku. The abrupt deforestation of Rano Aroi coincided with the Raraku LIA drought (Rull *et al.*, 2015).

(3) Climate-human-landscape interactions

The available empirical evidence of climate shifts (mostly droughts), spatiotemporal deforestation patterns and trends, and human presence and activities can be integrated into a holistic, nondeterministic scenario of Easter Island deforestation and its potential causes (Fig. 9). It is hoped that further research will improve this framework, but a synthesis of the information available to date seems pertinent to provide a unified multi-hypothesis research framework for future studies. The following is a proposal in this sense, which is subdivided into two main phases: the pre-Polynesian settlement phase (before 800-1200 CE) and the last millennium.

(a) Pre-settlement phase

This is still a very enigmatic phase, as the existing evidence is scarce and the possible interpretations are varied and somewhat speculative. The first record of forest clearing in Raraku dates to 450 BCE, but the disturbance, albeit maintained, remained of low intensity until ~1200 CE. During this very long phase (almost 1700 years), meadows slightly expanded, but the landscape continued to be forested. The appearance of *Verbena*, the gentle fire increase and the lack of evidence of climate change on the island were interpreted by Cañellas-Boltà et al. (2013) in terms of an anthropogenic disturbance, possibly by Amerindian people. However, the possibility of *Verbena* reaching the island by long-distance dispersal without human mediation cannot be ruled out. In addition, gentle charcoal increases with no signs of human disturbance during the Holocene have been found on other Pacific islands (e.g., Stevenson, 2004). The next deforestation event (by 100 CE) was recorded at Rano Kao and was linked to a conspicuous fire increase, suggesting human disturbance of unknown origin (Butler & Flenley, 2010). Again, no evidence of local climatic change was recorded. By those times, Rano Aroi was not forested, but the occurrence of *Sisyrinchium* since 450-650 CE could be used to reinforce the hypothesis of Amerindian presence (Horrocks *et al.*, 2015). Again, natural long-distance dispersal should not be dismissed. Another argument against an early Amerindian discovery of Easter Island is the lack of archaeological evidence for the time interval prior to Polynesian settlement. It could be argued that, during this phase, human presence was sporadic and/or intermittent, and a true autochthonous culture was not established. Another possibility is that American plants were not introduced by Native Americans but by people from other Pacific islands – possibly of the Lapita culture, which was well established in the central Pacific islands by those times (Kirch, 2010) – in eventual back-and-forth voyages to South America. Such an explanation has been proposed for the introduction of sweet potato to Polynesia (including Easter Island), and the cases of *Verbena* and *Sisyrinchium* could be similar. In this case, the first deforestation steps could have also been caused by ephemeral Lapita settlements. The available evidence is not enough to unequivocally support or reject either of these possibilities, which should be considered as working hypotheses for further studies. Regardless of the explanation, it seems clear that the full occupation of the island and the development of an island-wide autochthonous culture did not occur until the last millennium, when Polynesians permanently settled on the island, as demonstrated by archaeological evidence (Flenley & Bahn, 2003; Hunt & Lipo, 2006, 2011; Vargas et al., 2006; Wilmshurst et al., 2011).

(b) The last millennium

After a long period (~400-600 years) of apparent forest stability – or lack of evidence of forest disturbance, the first deforestation pulse during or after Polynesian settlement was detected in Rano Kao to be at ~1050

CE (Rull *et al.*, 2018; Seco *et al.*, 2019). The occurrence of spores of *Sporormiella* – a genus of coprophilous fungi living in the dung of domestic herbivores (Van Geel *et al.*, 2003) - suggests human presence. However, the small number of these spores and the absence of fire indicate that human occupation may have been low and probably not enough to cause a deforestation event similar to that recorded. This occurred during the MCA drought that desiccated Lake Raraku, and hence, the climate may have been the main factor responsible for the 1050 CE Kao forest clearing. The fact that Rano Aroi vegetation was apparently not affected by this drought could be due to the maintenance of wetter conditions due to higher elevation and the occurrence of an elevational precipitation gradient, which today is almost 200 mm/100 m of elevation (Puleston *et al.*, 2017). This local deforestation event occurred during the phase of low-intensity forest disturbance proposed by Mieth & Bork (2015), in which Polynesians settled the island by 800 CE, and more than a century before the dates proposed by the defenders of a late colonization, in 1200 CE or after (Hunt & Lipo, 2006; Wilmshurst et al., 2011). According to Nunn (2007), the discovery and settlement of Easter Island occurred during the MCA (also known as the Medieval Warm Period), between 750 CE and 1250 CE, when climatic conditions and rising sea levels would have favoured long-distance navigation among Polynesian archipelagos.

The next deforestation episode occurred in Raraku at ~1200 CE, just after the MCA drought, under sustained, although moderate, fire pressure (Cañellas-Boltà *et al.*, 2013). The occurrence of wetter climates more favourable for forest growth suggests that this deforestation pulse was of anthropogenic origin. Forest retreat was continuous despite fires not significantly increasing, which suggests the existence of positive feedbacks amplifying forest responses to sustained fire incidence. At the same time, the Kao forests were recovering, likely due to favourable climates and the absence of human pressure, as indicated by the lack of fires and coprophilous fungi (Rull *et al.*, 2018; Seco *et al.*, 2019). However, this forest regeneration was interrupted by another deforestation episode (1350 CE), likely anthropogenic, coinciding with a charcoal peak and the return of *Sporormiella* spores (Rull *et al.*, 2018; Seco *et al.*, 2019). Rano Aroi continued to be devoid of humans, and the significant forest expansion recorded between approximately 1300 CE and 1500 CE was likely due to the occurrence of wetter climates (Rull *et al.*, 2015).

Rano Raraku forests disappeared after a final deforestation event by 1450 CE, coinciding with significant fire exacerbation supporting human deforestation (Cañellas-Boltà *et al.*, 2013). At the same time, human pressure declined in Rano Kao, and its forests, which had been almost removed by the 1350 CE deforestation pulse, experienced a new regeneration trend, although less intense than the former (Rull *et al.*, 2018; Seco *et al.*, 2019). At the same time, Rano Aroi was truly forested for the first time, and its forests became the most dense and extensive on the island due to the almost complete deforestation of Raraku and Kao. However, the situation changed by 1570 CE, when a sudden deforestation event completely removed these forests (Rull *et al.*, 2015). This coincided with intense fire exacerbation, suggesting anthropogenic causes; however, the LIA drought would have acted synergistically by favouring forest flammability and preventing regeneration.

The last deforestation event on the island irreversibly removed the Kao forests by 1600 CE, coinciding with the largest human occupation of this crater, as indicated by the significant increase in fires and *Sporormiella* spores. This has been associated with the foundation of the ceremonial village of Orongo at the crest of the Kao crater, which took place at 1600 CE (Robinson & Stevenson, 2017) and replaced the Raraku quarry as the centre of the prehistoric Rapanui culture. This geographical shift coincided with the end of the Moai Cult and the onset of a completely different social, religious and political organization known as the Birdman Cult (Rull, 2016a; Rull *et al.*, 2018). It has been proposed that synergies between climate (drought and lake desiccation) and humans (deforestation) would have transformed the site into inhospitable badlands unable to support human activity and the moai industry, which was the main activity of the Rapanui civilization at

the time. This would have caused massive human migration to Rano Kao, likely the only freshwater source during the LIA drought (Rull, 2019b).

Taken globally, the intensification of deforestation between ~1200 CE and the total disappearance of forests by ~1600 CE coincided with the flourishment of the ancient Rapanui culture (Fischer, 2005; McCall, 2009) and with the phase of forest clearing exacerbation formerly proposed by Mann et al. (2008) and Mieth & Bork (2015), among others. However, the detailed reconstruction shown here, based on continuous sedimentary records from the three basins suitable for paleoecological study, significantly increases the spatiotemporal resolution and provides much more detail on the patterns, processes and possible causes of the different forest removal and regeneration events.

A comment on the possibility of Pacific rats being responsible for deforestation by preventing forest regeneration seems pertinent. This possibility was first suggested by Dransfield et al. (1984) and then by Hunt (2006, 2007) based on the finding of endocarps of the enigmatic palm species with marks of rat gnawing. Mieth & Bork (2010) attributed this to the fact that these palm endocarps were found exposed in caves and thus accessible to rats for a long time. These authors analysed endocarps buried in situ within charcoal layers, and only 10% had gnaw marks. Mieth & Bork (2010) also found evidence for forest regeneration in a second generation of palm root casts overlying an older layer with charred wood resulting from an earlier forest clearing dated to 1280-1390 CE. They concluded that rats did not hinder forest regeneration and, hence, were not responsible for Easter Island's deforestation. Palynological evidence of forest regeneration found in Rano Kao and Rano Aroi, as reported in this paper (Butler & Flenley, 2010; Rull *et al.*, 2015, 2018; Seco *et al.*, 2019), is consistent with Mieth's & Bork's (2010) conclusions.

VI. CONCLUSIONS

(1) The deforestation of Easter Island was not abrupt, synchronous and island-wide, as proposed by pioneer palaeoecological studies. Such earlier conclusions were based on the study of incomplete palaeoecological records consisting of sedimentary sequences containing a stratigraphic gap that hid the vegetation and landscape shifts of the last millennia. Recently recovered continuous (gap-free) sedimentary sequences including the last millennia, along with edaphic evidence of slash-and-burn events, have provided a different picture of Easter Island's deforestation, showing that forest removal on Easter Island was a largely heterogeneous process in time and space.

(2) Deforestation timing and rates were significantly different across the island. In Raraku, forest clearing started ~450 BCE and was not completed until approximately 2000 years after. This long and gradual process was spiked by two acceleration events that occurred at ~1200 CE and ~1450 CE. In Aroi, forest removal was abrupt and took place in less than a century, between ~1520 and ~1600 CE. In Kao, deforestation started at 50-100 CE and ended at ~1600 CE, with two main intermediate accelerations at ~1050 CE and ~1350 CE.

(3) Phases of forest expansion and regeneration were observed in Aroi and Kao but not in Raraku, where forest removal was a continuous process. In Aroi, forests expanded between ~1400 CE and ~1500 CE, whereas in Kao, three phases of forest recovery were recorded after the deforestation accelerations occurred at 50-100 CE, ~1050 CE and ~1350 CE. These observations indicate that deforestation pressure was not homogeneous across the island.

(4) Some deforestation events could be linked to droughts, others to human activities and others to feedbacks and synergies between them. Especially significant were two secular-scale droughts that occurred

during the Medieval Climate Anomaly and the Little Ice Age, which significantly reduced freshwater availability and likely prompted intra-island human migrations in the search for better living conditions. Frequent fires and land use in the form of small but widespread cultivation sites were the main anthropogenic activities linked to deforestation.

(5) The reviewed archaeological evidence for prehistoric agriculture suggests that total island deforestation did not cause a cultural collapse. The ancient Rapanui civilization was resilient to forest clearance, as shown by the continuity of agricultural practices in both drylands and lake terraces. Land use did not experience significant declines, and the Rapanui civilization underwent a major cultural change but remained healthy until European contact.

(6) In summary, Easter Island deforestation appears to have been a heterogeneous process in time and space under the influence of both natural and anthropogenic drivers, which did not cause a cultural collapse. The whole picture contrasts with the former ecocidal paradigm of an island-wide abrupt forest clearing caused exclusively by humans and opens a new, more complex perspective on forest removal and its causes, as well as the potential consequences for the Rapanui culture.

VII. FURTHER RESEARCH

Further palaeoecological efforts are still needed for a sound understanding of the timing and patterns of Easter Island deforestation and its causes. Regarding coring, only one continuous and chronologically coherent sedimentary sequence is available for the last millennium at each site, and more coring is required to confirm the first insights based on these sequences. The recent development of molecular analyses, especially biomarkers, may provide valuable information on climatic shifts and human activities. For example, the use of glycerol-dialkyl-glycerol-tetraethers (GDGTs) and *n*-alkanes from plant leaf waxes may provide detailed temperature and precipitation reconstructions, respectively (Eglington & Eglington, 2008). Regarding human presence and activities, the use of specific faecal lipids such as 5α-stanols and bile acids can reveal the presence of humans and/or ruminant livestock (Bull, 2002; D'Anjou *et al.*, 2012). Molecular DNA analyses may also provide evidence of anthropogenic activities by directly recording human presence and the occurrence of plants and animals associated with human activities (cultivation, livestock, and introduction of alien species) (Rawlence *et al.*, 2014; Parducci *et al.*, 2017). This is especially useful to complement pollen and other microfossil analyses (fungal spores, phytoliths, and starch) and could provide crucial evidence for the identification of the unknown palm species that dominated Easter Island forests. Infrared spectral analyses (FTIR) have also been useful for microfossil identification in Easter Island sediments, but their full potential has not yet been fully realized. This is also a growing field of research that should be intensively used in the future. In addition to new coring campaigns and the use of novel molecular evidence, multidisciplinary collaboration is essential, not only within the different palaeoresearch specialties but also among different scientific disciplines such as archaeology, anthropology, ethnology and history, among others (Rull *et al.*, 2013). A constant in Easter Island research has been the individualistic behaviour of these disciplines, which is contrary to the integrative nature of palaeosciences and the complexity of environment-landscape-human interactions (Rull, 2018). Truly multidisciplinary studies are essential for progressing towards a sound understanding of what truly happened on Easter Island before European contact.

VIII: ACKNOWLEDGMENTS

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Figure captions

1. Location map. A) Sketch map of the main Pacific islands and archipelagos, showing the position of Easter Island (red dot). West-east peopling trends from continental Asia are indicated by orange arrows (Kirch, 2010). B) Sketch map of Easter Island indicating the wetlands (ranos) cored for palaeoecological studies (blue areas). Present-day planted forests, mainly of *Eucalyptus* (Myrtaceae), are indicated in green. Elevation in metres.

2. Moai complex of Ahu Tongariki, near Rano Raraku, with the Poike cliffs in the background. These moai are up to 9 m high and 90 tons in weight. Photo: V. Rull.

3. Google Earth images of the three ranos cored for palaeoecological analyses and their location on the island. The dark-green areas at the centre of the island are planted *Eucalyptus* forests. All cores retrieved historically from the three sites are shown (white dots), and the recent continuous and chronologically coherent sequences are highlighted by red dots and blue names. Redrawn from Rull (2016).

4. Selected representative pollen types from lake/marsh sediments. 1) Unknown palm species, 2) Poaceae, 3) Cyperaceae, 4) Compositae, 5) *Polygonum*, 6) *Triumfetta*, 7) and 8) *Verbena litoralis*. 1 to 6 are from Rano Aroi (Rull *et al.*, 2015), and 7 and 8 are from Rano Raraku (Cañellas-Boltà *et al.*, 2013).

5. Palm forests of Easter Island. A) Hypothetical reconstruction of ancient palm forests from Poike (drawing by Gerd Close). B) Palm forest of *Jubaea chilensis* from La Campana (Chile) (photo by A. Mieth). Images from Mieth & Bork (2010, 2012) by courtesy of A. Mieth.

6. Age-depth models of the continuous and chronologically coherent sedimentary records of the last millennia obtained in Rano Raraku, Rano Aroi and Rano Kao. Reproduced from Cañellas-Boltà *et al.* (2013) (Raraku) and Rull *et al.* (2015, 2018) (Aroi and Kao), with permission.

7. Synthetic diagrams of Rano Raraku, Rano Kao and Rano Aroi for the last millennium. Droughts are depicted as grey bands. Red triangles indicate deforestation pulses, and forest regeneration trends are indicated by blue arrows. Raw data and full diagrams are in Cañellas-Boltà *et al.* (2013) (Raraku), Rull *et al.* (2018), Seco *et al.* (2019) (Kao), and Rull *et al.* (2015) (Aroi).

8. Graphical representation of the strong fuzzy EHLFS approach for Easter Island's ecological and cultural changes (Rull, 2018). E – Environment, H – humans, L – landscape. Feedbacks are represented by blue arrows, and synergies, by red arrows. Grey arrows are internal feedbacks.

9. Spatio-temporal deforestation patterns of Rano Aroi, Rano Kao and Rano Raraku areas and their potential drivers after Polynesian settlement, using the information in Fig. 7. Forest cover was estimated by palm pollen percentage. The blue arrow indicates the migration of the cultural core of the Rapanui society from Rano Raraku to Rano Kao. See text for detailed explanations.
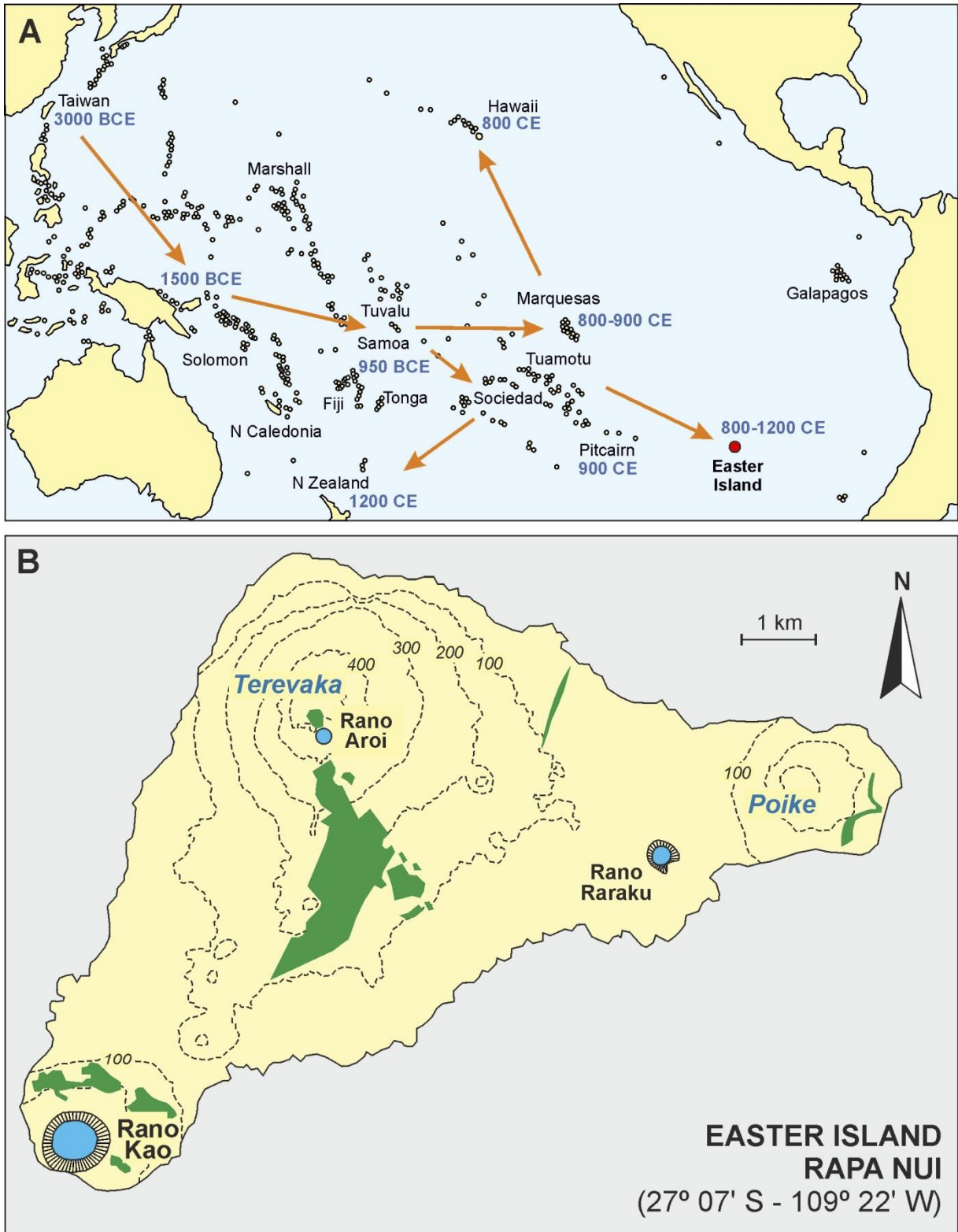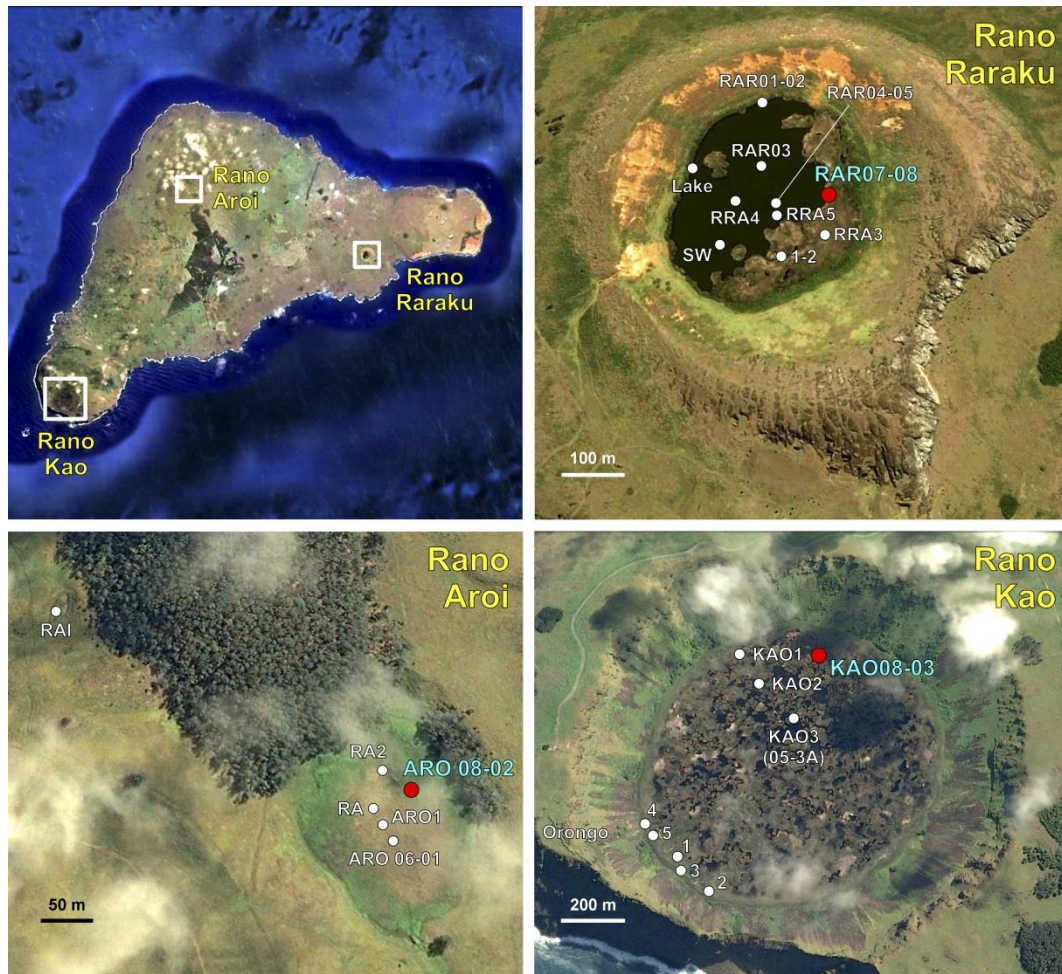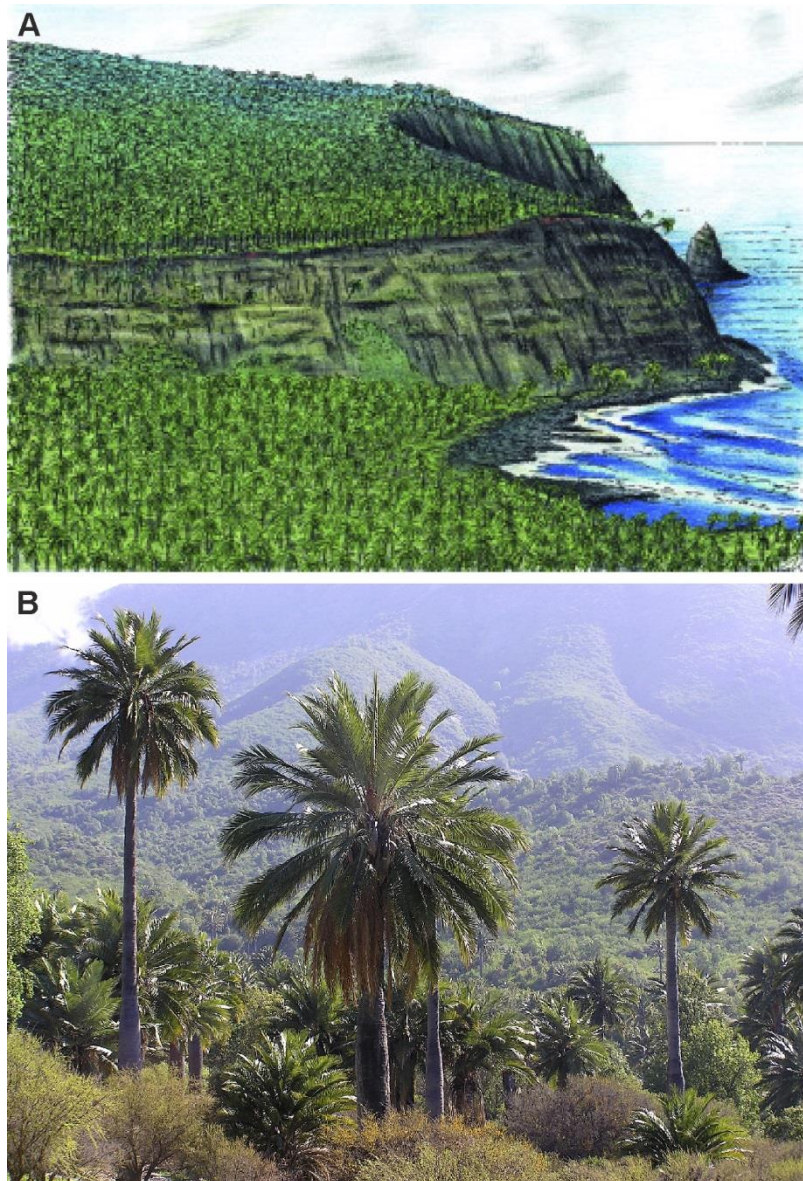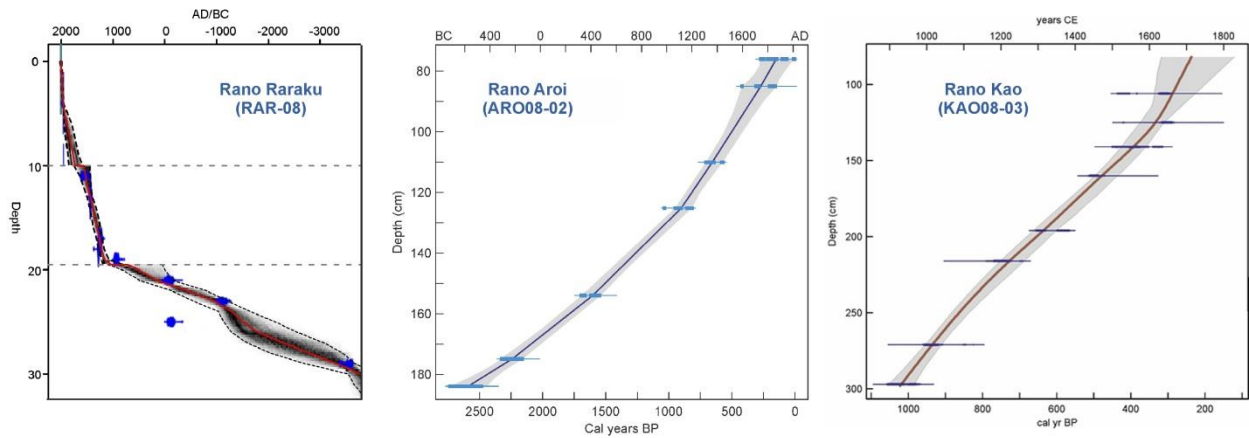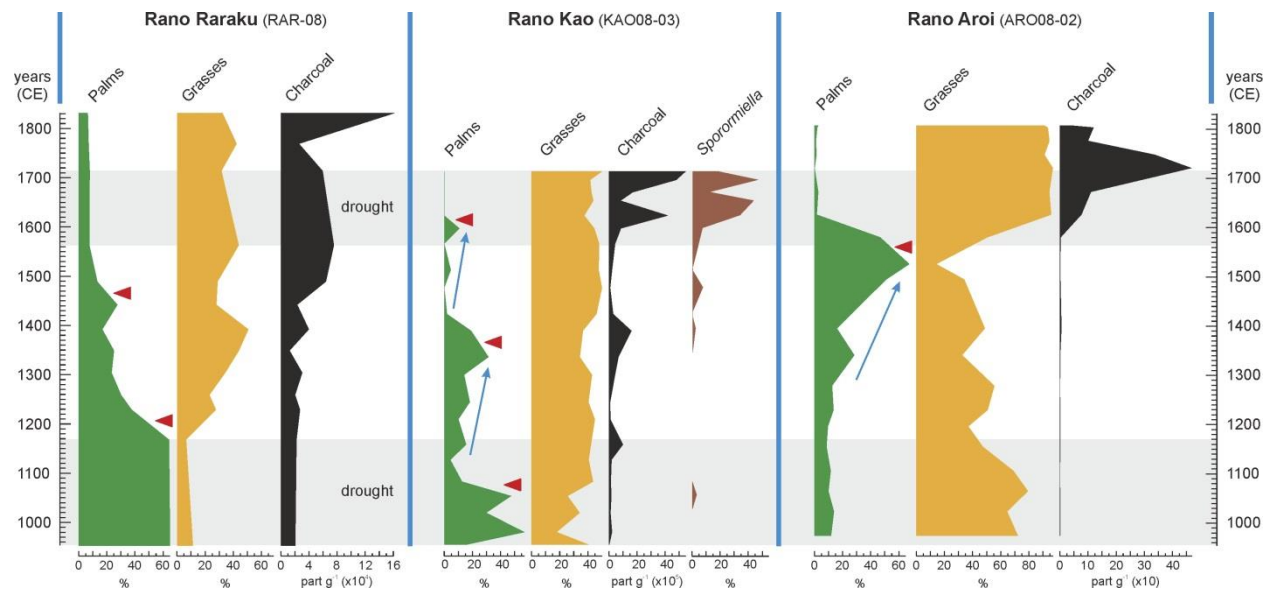
Figure 1

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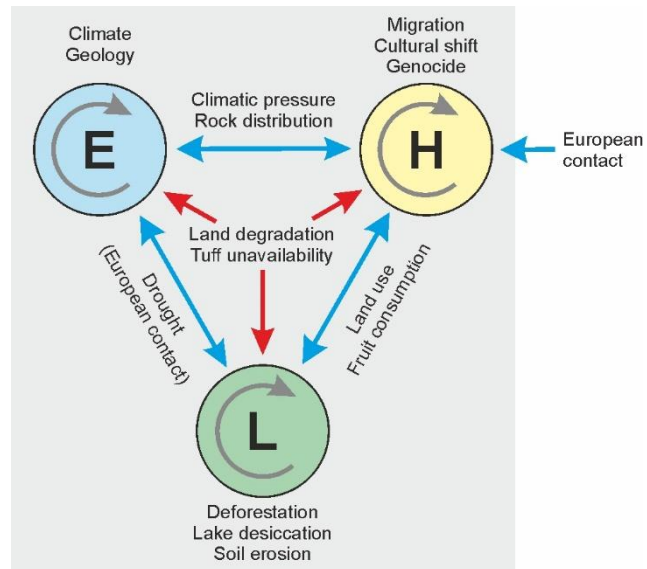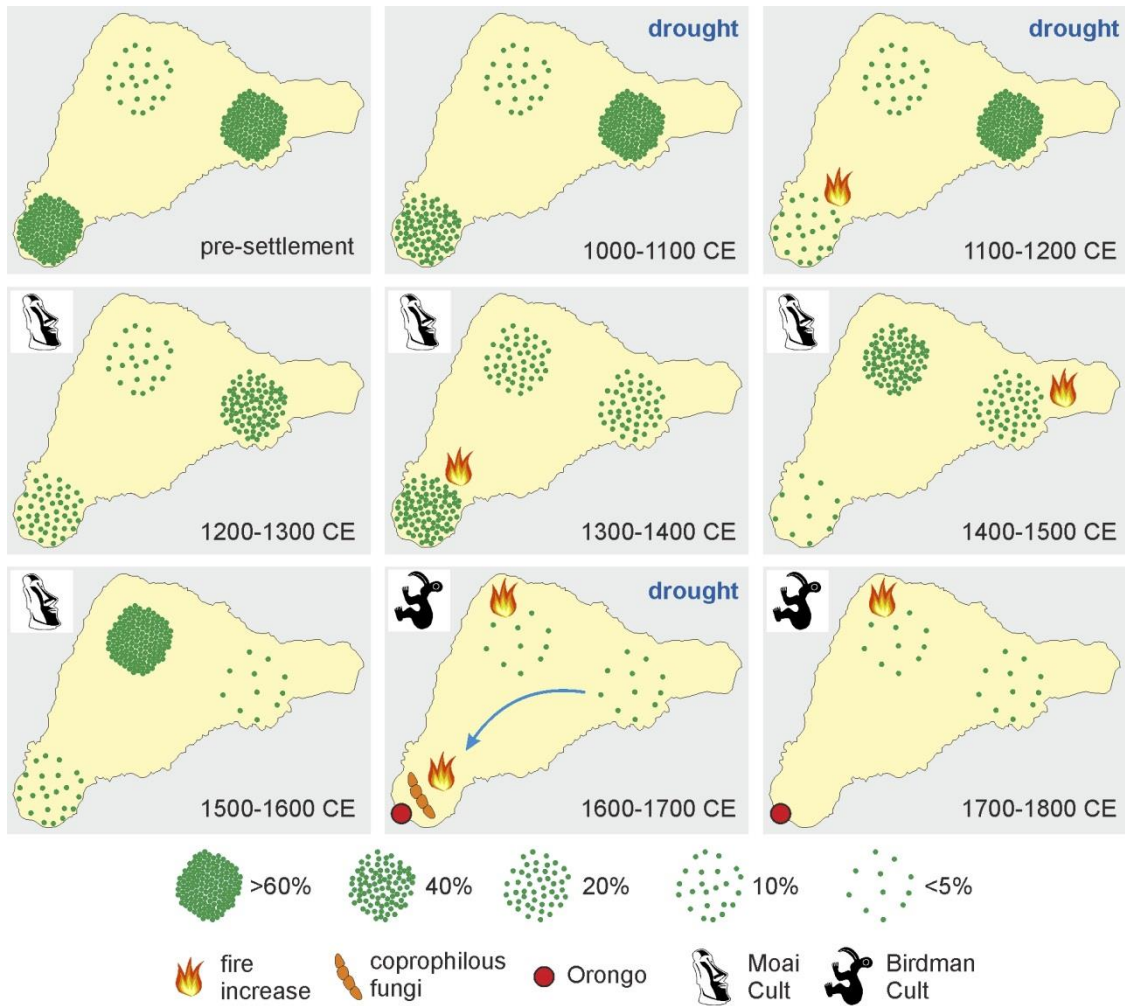Figure 7

Figure 8

Figure 9